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Sub–parsec to Mega–parsec jet emission and power

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Abstract. Relativistic jets carry a significant fraction of the total energy budget of a radio source, rivaling the power that is extracted through accretion. A minor part of this bulk kinetic power is transformed to radiation, possibly through internal shocks if the plasma is accelerated, at the base of the jet, to a velocity which changes in time. In this way we can understand why some radiation is produced all along the jet even if most of it originates at a preferred location, and why the efficiency of conversion of bulk to random energy is small. The recent observations by Chandra of intense jet X–ray emission at large scales suggest that at least the "spine" of jets continues to be highly relativistics even up to hundreds of kiloparsecs away from the nucleus and give tight lower limits on the jet bulk kinetic power.

1. Introduction

The formation, acceleration and collimation of extragalactic jets is still an open issue, despite several years of active research, and despite the great amount of information provided by improved VLBI techniques from the ground and now from space, and the detection of jets in the optical and X–ray bands. We still do not know the amount of power that the jets must carry and their matter content.

Radio lobes, acting as calorimeters, should be the best site to measure the average energy supply, but even in this case the estimates depend on the uncertain assumption of equipartition and on the unknown amount of the proton contribution to the total energy and pressure (Rawlings & Saunders 1991).

The alternative is to measure the kinetic jet power $L_{\rm jet}$ directly, taking advantage of the apparent superluminal speeds measured in blazars to estimate their bulk Lorentz factor, and the minimum amount of leptons required to account for the observed emission. This has been done by Celotti & Fabian (1993) using radio data on the milli–arsec scale (corresponding to a linear scale of the order of a parsec). Recently, the discovery that blazars are strong γ–ray emitters provided a new tool to measure $L_{\rm jet}$ on the sub–pc scale, and, even more recently, the discovery of relatively strong large scale X–ray jets by Chandra allowed yet another method to estimate $L_{\rm jet}$, this time on the 100 kpc – Mpc scale.

The last two methods are based on spectral modeling of the spectral energy distribution (SED) of blazars, giving the relevant estimates on the size, magnetic field, particle density, and bulk Lorentz factor, necessary to calculate $L_{\rm jet}$, as detailed below. For the implications regarding the jet formation mechanism see Maraschi, these proceedings.

2.   Sub–pc scales

Consider the properties of small scale jets, i.e. on a scale corresponding to the production of most of the blazar emission. This scale has to be of order 10^{-2} – 10^{-1} pc. It cannot be much smaller than this because of the required transparency of the source to the observed energetic γ–rays (for the $\gamma\gamma \to e^{\pm}$ process) and it cannot be much greater to account for the observed short variability timescales (Ghisellini & Madau 1996). What can we infer on such scales?

Good spectral coverage of the broad band SED of a large number of blazars have allowed to characterize the spectral properties of such objects: two broad peaks characterize the blazar SED, and their peak frequencies and intensities define different blazar subclasses (Padovani & Giommi 1996). Systematic trends in the SED have been then found (Fossati et al. 1998): both peak frequencies decrease for increasing bolometric power, and at the same time the high energy component becomes more dominant.

Recently, such a systematic behavior has been re-examined and compared with the results obtained from the hard X–ray energy band of a large number of blazars (Donato et al. 2001). In general a good agreement between the expected trend and the observed properties in the hard X–rays is found, although a quantitative modification in the functional dependence of the spectral characteristics on the power has been suggested (Donato et al. 2001). In Fig. 1 we report the SED of blazars where data in each band corresponds to the average luminosity of sources binned according to their radio power (as derived by Fossati et al. 1998), with added the new hard X–ray information and the analytical parametrization of the SED proposed by Donato et al. (2001).

From the interpretational point of view, information on the high energy component (most notably on the copious γ–ray emission) have prompted the formulation of scenarios for the production of the blazar broad band spectrum (e.g. Sikora, Begelman & Rees 1994; Sikora 1994 and references therein). The phenomenological trends just discussed have been considered within such models. More specifically Ghisellini et al. (1998) have inferred physical properties of the sources from the modeling of a large number of blazar SED. The assumed scenario postulates that the emission is due to the synchrotron and inverse Compton processes (where the latter one acts on both the synchrotron photons themselves and any other externally produced radiation field) from a relativistically moving homogeneous source.

2.1.   The power of jets at the sub–pc scale

Within such scenario, it is possible to estimate the relevant physical parameters of the emitting region, such as the size and beaming factor, the magnetic field and the density of the emitting particles. Therefore it is possible to calculate the flux of bulk kinetic and magnetic energy transported by the jet. It turns out
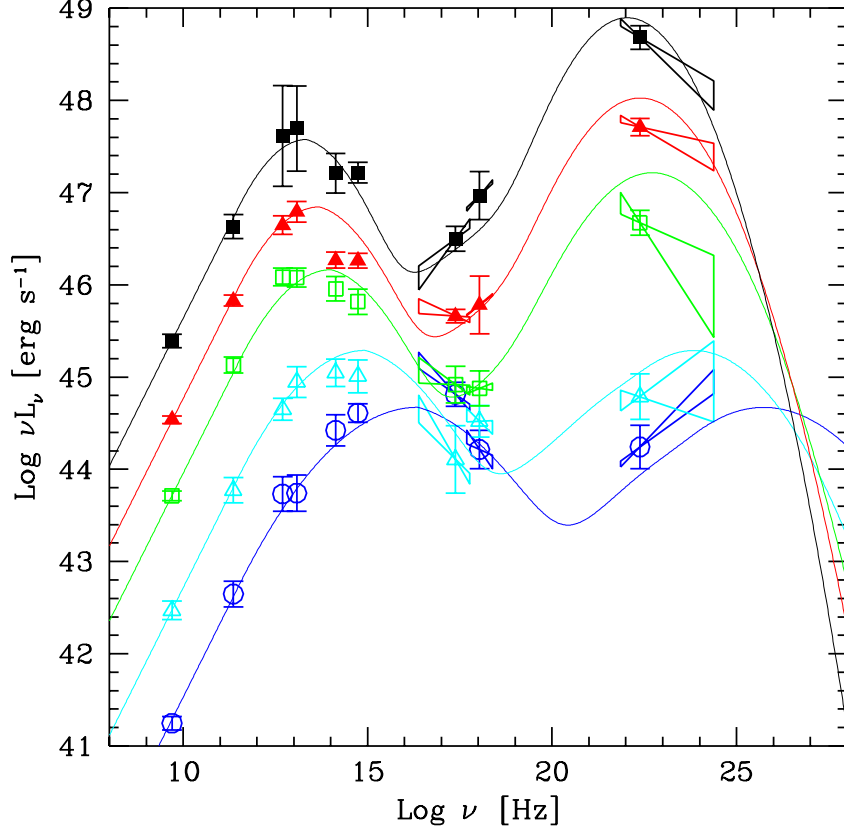
Figure 1. Averaged SED of blazars. The data in each band are the result of averaging over a number of sources, belonging to the 1 Jy complete sample of BL Lacs, the Einstein SLEW survey sample of BL Lacs and the 2 Jy complete sample of blazars, for a total of over 100 sources. The sources have been divided into 5 bins of increasing radio power, thought to be representative of the bolometric one. See Fossati et al. (1998) and the additional new collection of hard X–ray data in Donato et al. (2001). The solid curves correspond to a phenomenological description of the average SED which is based on only one parameter (which can be the bolometric power, the peak synchrotron frequency or the radio power, which are related with one another through simple relations), as discussed originally in Fossati et al. (1998) and slightly modified by Donato et al. (2001).

that relativistic jets carry a significant fraction of the total energy budget of a radio source, rivaling the power that is extracted through accretion. In fact the bulk kinetic power of the emitting plasma largely exceeds the radiated one (see Fig. 2; Celotti & Ghisellini, in prep). Such low efficiency of conversion of bulk to random (and then to radiative) energy is indeed expected if the dissipation is driven by the formation of internal shocks, e.g. as those which would occur if the plasma is accelerated, at the base of the jet, to a velocity which changes in time (Ghisellini 1999; Spada et al. 2001). This plausible dissipation mechanism also naturally provides a preferred spatial location where the bulk of the radiation is produced (Rees 1978), similar to the one inferred from the arguments on source transparency to γ–rays and variability.

2.2. Electron–positron pairs?

A further interesting point which can be inferred from the estimated powers is the negligible role played by electron–positron pairs as jet energy carriers. In fact, as shown in Fig. 2, the kinetic power associated with the relativistic emitting particles appears to be insufficient to provide the dissipated luminosity. A caveat should be discussed, namely the possible presence of particles emitting at energies below the observed frequency band, i.e. the extension/shape of the relativistic particle distribution to low energies, which can constitute a crucial uncertainty in the estimate of the bulk kinetic power (and thus the radiative efficiency) of jets at the sub–pc scale. As the particle distribution is typically steep, the particle number density – and thus the bulk energy carried by the particles – is crucially dependent on it (this is typically parametrized by the lower Lorentz factor of such energy distribution, γ_{min}).

The good quality data in the soft X–ray band of powerful radio loud quasars provide tight limits on such quantity. If indeed – as widely believed – the X–to-γ– ray component in such sources is dominated by the inverse Compton scattering of externally produced photons (such as broad line or disk photons) the soft X–ray spectrum is dominated by the photons scattered by the lowest energy relativistic particles. The shape of the spectrum in this band allows then to determine the shape/extension of the lower end of the emitting particle distribution. As shown in Fig. 3 for one of the few blazars with data good enough to accurately model the soft–medium X–ray emission, the soft spectrum typically limits γ_{min} to be of order unity.

A second argument against a significant dynamical contribution of electron– positron pairs in powerful radio–loud quasars derives from the difficulty of producing them in sufficient number at the relevant emitting jet scales. If pairs were produced in the inner compact source, the surrounding intense photon field rapidly cools them, enhancing the annihilation rate. The resulting surviving pairs, which can propagate along the jet, are numerically not enough to account for the required power (which has to exceed the radiated one) (Ghisellini et al. 1992; Celotti & Ghisellini, in prep). Alternatively, pairs could be created along the jet and/or in the γ–ray emitting region itself. However, significant reprocessing of γ–rays into electrons and positrons would also lead to a copious emission from the pairs themselves in the X–ray band, well in excess of the observed X–ray flux (Ghisellini & Madau 1996).
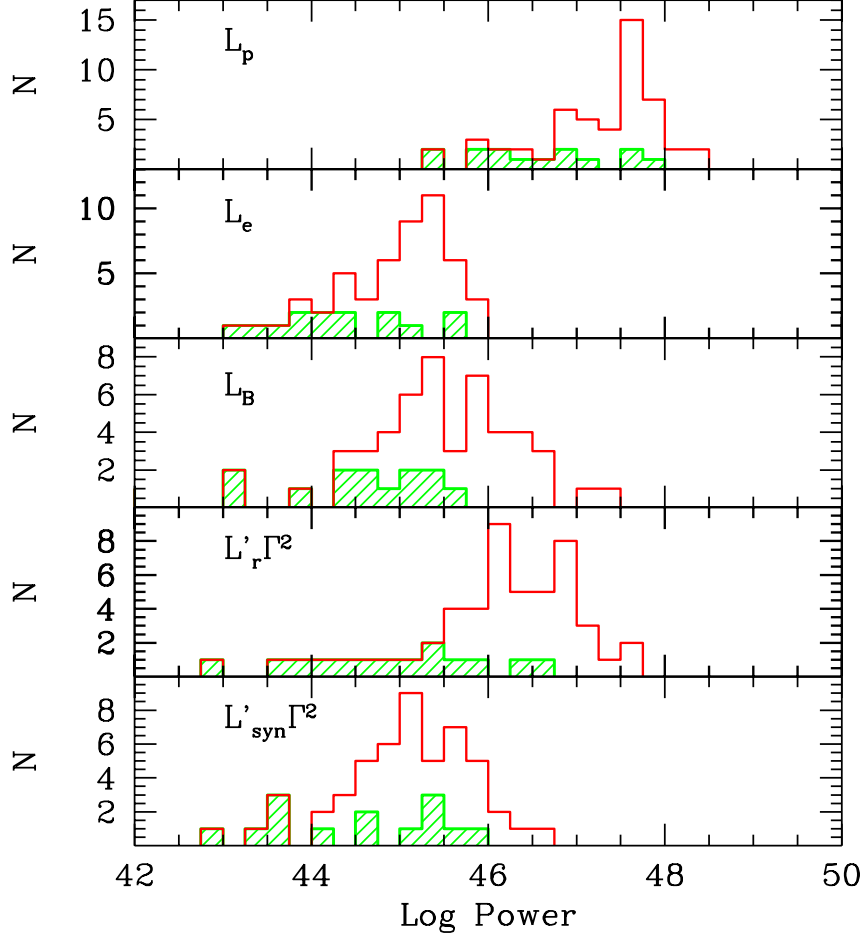
Figure 2.   Histograms of powers estimated for flat spectrum radio loud quasars and BL Lac objects (the latter ones represented by shaded areas. Powers are in erg s^{-1}). $L'_r\Gamma^2$ and $L'_{syn}\Gamma^2$ represent the total and the synchrotron radiative power dissipated in the jet, respectively (where Γ is the bulk Lorentz factor), while L_e, L_p and L_B indicate the kinetic powers associated with the electron component, the proton component (assuming one proton per electron), and the power transported as Poynting flux, respectively. The relative quantities are estimated by modeling the observed SED of blazars as due to synchrotron and inverse Compton emission from a homogeneous one–zone region (see Ghisellini et al. 1998 for details on the model). From Celotti & Ghisellini, in prep.

Note that these arguments imply that it is unlikely that the jet plasma is dynamically dominated by pairs (i.e. that the kinetic luminosity in pairs provides the bulk of the jet energy transport) but do not exclude that (a smaller number of) pairs can contribute to the emission. In particular the ratio of the proton power to the radiatively dissipated one allows only < 10 pairs per electron/proton to be present. It is also worthwhile to stress that the limits imposed by the presence of a high external radiation field do not strictly apply to the weakest blazars (BL Lacs), for which there is no strong direct evidence for the presence of a large density of external photons.

2.3. What controls the blazar SED?

A further piece of information recently emerged from the modeling of the SED and the X–ray observations (by *Beppo*SAX) of the most extreme, faintest, highly energy peaked BL Lacs. For the rest of the blazar population – as for the sample considered in Ghisellini et al. (1998) – a clear correlation was found between the energy of particles emitting at the energy peaks of the spectrum, γ_{peak}, and the energy density U (in magnetic plus radiative fields), namely $\gamma_{peak} \propto U^{-0.6}$. However, when extreme highly peaked BL Lacs (some of which detected in the TeV energy band) are also considered, such correlation significantly steepens, becoming $\gamma_{peak} \propto U^{-1}$ for small values of U. The observed $\gamma_{peak} \propto U^{-1}$ behavior, for these blazars, is consistent with the internal shock scenario, where the particle injection mechanism is not stationary, but impulsive, and it lasts for a timescales comparable for the time needed to one shell to cross the other. During this time only the highest energy electrons radiatively cool, steepening only the high energy part of the injected particle spectrum. The rest of it retains its original slope. In this case γ_{peak} does not correspond to the minimum energy of the injected electrons (as is the case for more powerful sources), but to the energy for which $t_{cool}(\gamma) = t_{injection}$ (Ghisellini & Celotti, in prep).

3. Mpc–scales

Radio, optical and X–ray observations have recently allowed huge progresses in the estimates and understanding of properties of large scale jets. Most notably the detection by Chandra of intense X–ray emission at 100 kpc–Mpc scales has opened a new window to study the energetic and physical processes occurring in jets and their interaction with the environment.

In particular the X–ray data of the first detected source (PKS 0637–752) and their comparison with information on similar scales and at similar resolution in the radio and optical bands, support the view that the X–rays are produced by inverse Compton scattering of relativistic electrons against the cosmic microwave background radiation (CMB). Alternative interpretations appear in fact to require more contrived conditions of the jet plasma (e.g. Schwartz et al. 2000; Celotti, Ghisellini & Chiaberge 2001; Tavecchio et al. 2000b). The dominance of scattering on the CMB however requires that at least part of the emitting plasma is moving at highly relativistic speeds not only at sub–pc and pc scales, but up to hundreds of kiloparsecs away from the nucleus. This possibility appears to be at odds with radio observations implying at most only moderately relativistic velocities on the largest observed scales (such as the presence of both
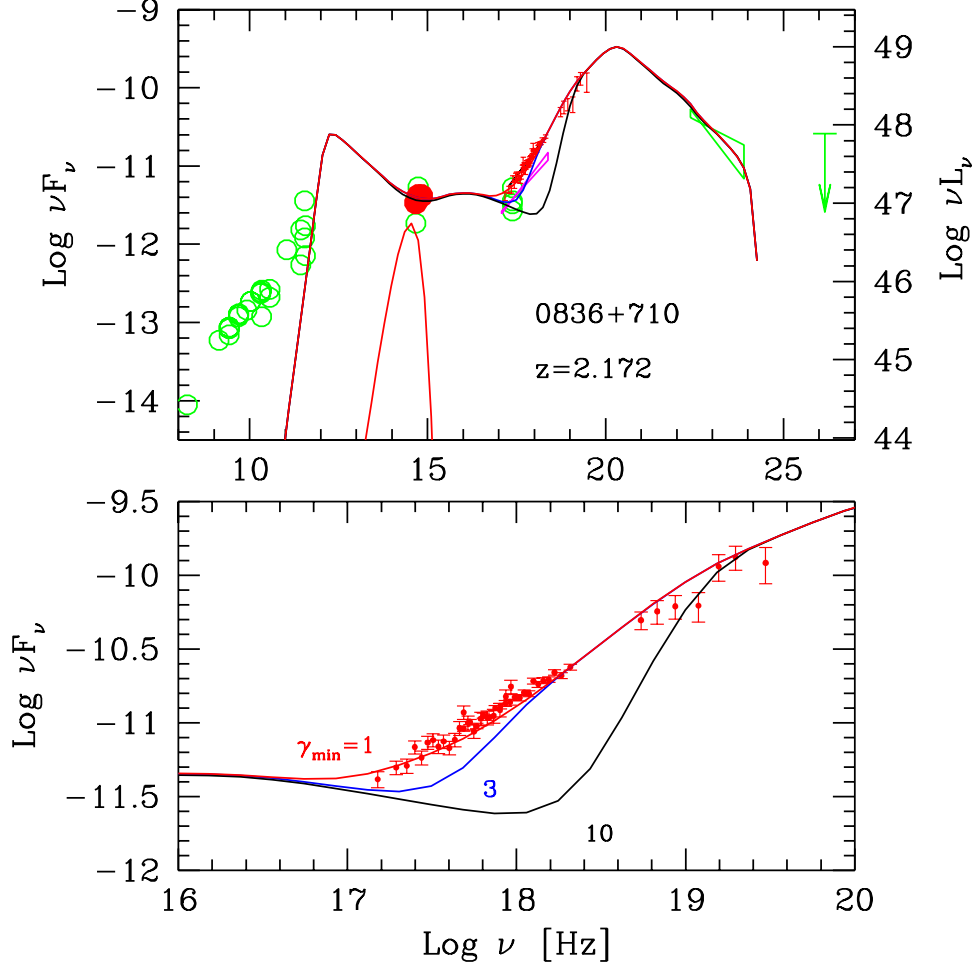
Figure 3. The SED and a zoom on the X–ray spectrum (*Beppo*SAX data, Tavecchio et al. 2000a) of the blazar 0836+710 (upper and bottom panel, respectively). The lines represent the predictions from a model assuming that the two spectral components are synchrotron and inverse Compton emission (both synchrotron self–Compton and scattering of an externally produced photon field, schematically represented as a peaked blackbody component) from a homogeneous source (see Ghisellini et al. 1998 for more details on the model). In particular in the bottom panel the model predictions are reported for different values of the lower Lorentz factor of the emitting particle distribution, γ_{min}, which thus results well constrained by the soft X–ray data to values of order unity. Note the hard X–ray emission dominates the power output (see the right y–axis of the upper panel).
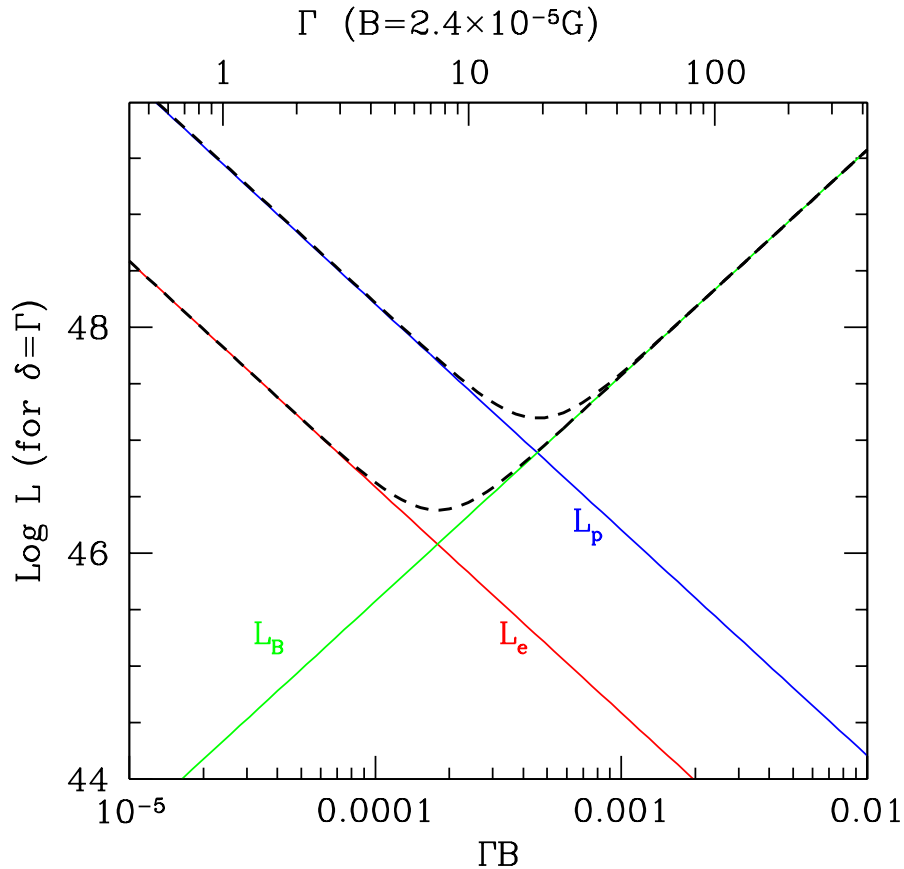
Figure 4.   Kinetic powers carried by protons (L_p), emitting electrons (L_e), and Poynting flux (L_B), as inferred from the large scale emission of the quasar PKS 0637–752 as functions of the product of the bulk Lorentz factor and magnetic field (ΓB). The Doppler factor δ is assumed to be equal to the bulk Lorentz factor Γ, implying a viewing angle equal to $1/\Gamma$. The electron number density carried by the jet is estimated through the observed synchrotron luminosity. The kinetic powers $L_{e,p} \propto (\Gamma B)^{-2}$, while the Poynting flux $L_B \propto (\Gamma B)^2$. For L_p we assume one proton per electron. The upper x–axis reports the values of Γ assuming the indicated magnetic field, resulting from fitting the observed spectrum (Celotti, Ghisellini & Chiaberge 2001). Note that the total transported power (sum of these components) is minimized for bulk Lorentz factors similar to those inferred on smaller scales, suggestively supporting the hypothesis that at least part of the plasma flowing on large scales moves at highly relativistic speeds. From Ghisellini & Celotti (2001b).

the jet and the counterjet). But in fact the two sets of (X–ray and radio) findings might be easily reconciled and indicate the presence of a velocity structure in the jet, with a fast "spine" surrounded by a slower "layer" – i.e. a velocity gradient in the radial direction (see also e.g. Laing 1993, Chiaberge et al. 2000).

3.1. The minimum power of large scale jets

Further support to the hypothesis that jets are still moving at highly relativistic speeds on the largest scales comes from estimates of the transported powers. In fact – at least for the best studied source so far, PKS 0637–752 – the constraints on the plasma parameters inferred from the broad band distributions relative to hundreds of kiloparsecs scale emission, show that the total power (kinetic plus electromagnetic) associated with the emitting plasma is minimized – for a given observed radiated luminosity – for bulk Lorentz factors of order $\Gamma \sim 10$–20. The argument is simple: from the observed synchrotron power $L_{\rm s}$ we can estimate the (comoving) density of the emitting particles $n' \propto L_{\rm s}/[B^2\delta^4]$. The bulk kinetic power is therefore proportional to $L_{\rm e,p} \propto \Gamma^2 L_{\rm s}/[B^2\delta^4]$, while the Poynting flux $L_{\rm B} \propto B^2\Gamma^2$. Here δ is the Doppler factor, which is equal to the bulk Lorentz factor for viewing angles close to $1/\Gamma$. In this case $L_{\rm e,p}$ and $L_{\rm B}$ behave in a opposite way with respect to ΓB and there is a minimum total power $L_{\rm e,p} + L_{\rm B}$ for some value of ΓB. Fig. 4 reports the luminosity in the proton, electron and magnetic field components (and their sum as dashed lines) as a function of ΓB.

Since the spectral fits yield an independent value of B, we can find the value of Γ which minimizes the jet power budget. The found value of Γ is fully consistent with those inferred from the spectral modeling and the jet speeds on nuclear scales (Ghisellini & Celotti 2001a), as shown in the previous section.

It should be finally stressed that – according to this scenario – information on the large scales provide tighter constraints with respect to the sub–pc scales on the power estimates, as in the former case the external radiation field intensity and spectrum (i.e. of the CMB) can be robustly estimated.

The presence of both a highly relativistic "spine" and a slower layer in large scale jets implies that both blazars and radio–galaxies are expected to copiously radiate in the X–ray band through the inverse Compton process. In the case of radio–galaxies, in fact, the slow layer can be illuminated by the boosted radiation coming from the nucleus, providing extra seed photons for the inverse Compton process contributing in the X–ray band (Celotti, Ghisellini & Chiaberge 2001). The emission from these slow layers is less beamed, and therefore visible also at large viewing angles (i.e. in radio–galaxies), while the strongly beamed emission from the spine is visible for aligned sources with a blazar–like core.

4. Are jets more powerful than accretion disks?

Rawlings & Saunders (1991) suggested that $L_{\rm acc} \sim L_{\rm jet}$ for the considered FR II and (a few) FR I radio–galaxies for which they could estimate the (minimum) total energy in the radio lobes and their lifetime, yielding the average power supplied by the jet, i.e. $\langle L_{\rm jet} \rangle$, and the luminosity in narrow emission lines, proportional to the ionizing radiation coming from the disk and hence to $L_{\rm acc}$. On the other hand there is little doubt that BL Lac objects (thought to be FR I pointing at us) are characterized by very weak or absent emission lines, invisible
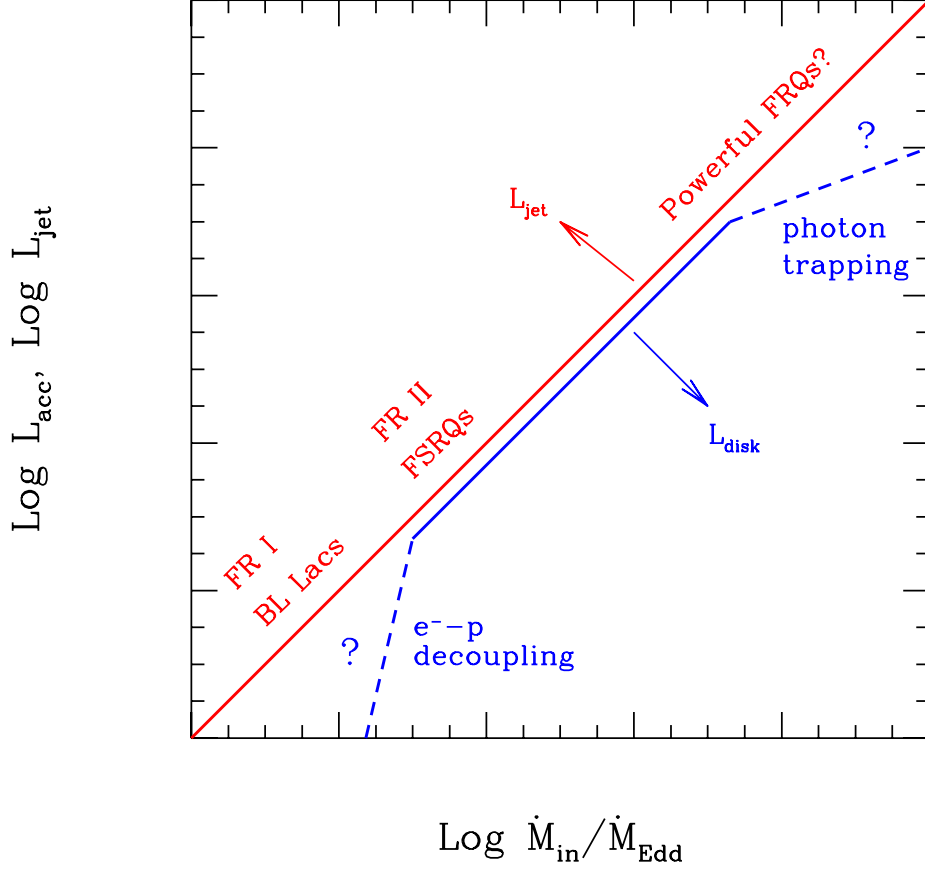
Figure 5.   Schematic diagram illustrating how the power of jets and of accretion could scale as a function of $\dot{m} = \dot{M}_{in}/\dot{M}_{Edd}$. Less powerful sources (BL Lacs and FR I radio–galaxies) lacking broad emission lines should be characterized by radiatively inefficient accretion disks (protons do not transfer efficiently their energy to electrons) and in these sources the jet power may be dominant. At the other extreme, at very large $\dot{m}$, the accretion disk could be again an inefficient radiator because of photon trapping, and again the jet could more powerful than the disk. At intermediate values of $\dot{m}$ the jet and accretion power are more or less equal, as found by Rawlings & Saunders (1991). The fact that $L_{jet} \propto \dot{M}_{in}$ is justified by the approximate equality between L_{jet} and L_{acc} for the sources considered by Rawlings & Saunders (1991), and by the fact that the bulk Lorentz factor of all jets as estimated by their superluminal velocities are distributed in a narrow range (see Jorstad et al. 2001).

blue bumps, and relatively powerful jets. For these objects therefore $L_{\text{jet}} > L_{\text{acc}}$. At the other, high power, end of the sequence, there is again the indication that $L_{\text{jet}} > L_{\text{acc}}$, at least in a few cases, such as PKS 0836+710. We have collected these hints (admittedly not yet a robust scenario) in a qualitative way in Fig. 5.

There are theoretical reasons to expect a deficit (with respect to a pure linear proportionality) in the power extracted by accretion and dissipated in the accretion disk at both power ends: at high power photon trapping may prevent the produced radiation to emerge from the accretion flow, and at low power the e–p decoupling can generate accretion disks which are inefficient radiators, such as ion supported tori (Rees et al. 1982), advection dominated accretion flow (ADAF, see e.g. Narayan, Garcia & McClintock 1997), adiabatic inflow–outflow (ADIOS, Blandford & Begelman 1999) or a convection dominated flow (CDAF, Narayan, Igumenshchev & Abramowicz 2000). *Jets could therefore be the most efficient engines,* and hints about their origin and acceleration may even come from Gamma Ray Bursts (GRBs), whose radiation is probably collimated as well in a sort of jet (or "flying pancake"). Their durations, in fact, indicate a relatively *long* process (10^4–10^5 dynamical times), and it may be that the same jet generation process is at work both in GRBs and radio–loud AGNs.

5. Conclusions

We are still looking for the basic numbers of jets: how much power they carry and what are they made of. Progress has been made recently, and more is expected soon, especially with high resolution observations in radio, optical and X–rays of the same jet structures.

For instance, recent X–ray observations of radio galaxies embedded in clusters are start showing (in a few cases so far) a close connection between the morphology of the relativistic lobe components and the external thermal cluster gas. The high resolution images allow to improve the estimates on the dynamical interaction of these two components which in turn give significant constraints on both the jet matter content and the filling factor of the relativistic plasma (Fabian et al. 2001). Complete disentangle of the values of these two quantities can be foreseen with forthcoming deeper observations.

Another advance within immediate reach is the knowledge of the central black hole mass through velocity dispersion and/or optical luminosity of the host galaxy (Ferrarese & Merrit 2000; Magorrian et al. 1998), allowing to measure the jet powers in units of the Eddington luminosity. This approach already allowed to interpret in a new way the division line between FR I and FR II radio–galaxies in the radio–host optical luminosity plane. This can be due to a change in the accretion power as measured in units of the Eddington one: radio–galaxies above a critical value are FR II, while FR I are characterized, on average, by larger masses and lower accretion rates (Ghisellini & Celotti 2001b). Finally, and related to the difference between FR I and FR II radio–galaxies, there might be important advances in numerical simulations, disclosing key features about shock physics and about the problem of how jets (in FR I sources) are decelerated.

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